NASA'S ULTRA-EFFICIENT ENGINE TECHNOLOGY (UEET) PROGRAM/AEROPROPULSION TECHNOLOGY LEADERSHIP FOR THE 21ST CENTURY

Robert J. Shaw
NASA Glenn Research Center
Cleveland, OH 44135

Abstract

One of NASA's four main product lines is developing and transferring to U. S. industry enabling technologies required for next generation aerospace vehicles as part of the Aerospace Technology Enterprise. This paper overviews the Ultra Efficient Engine Technology (UEET) Program, NASA's focused aerospace propulsion technology program. The UEET Program emphasizes technology development in six selected areas --low emissions combustion, highly loaded turbomachinery, high temperature materials and structures, intelligent propulsion controls, propulsion-airframe integration, and integrated component technology demonstrations. In addition, systems studies provide a system integration function for the UEET program to ensure that proper investments in technology are made. The paper overviews the content of each element of this UEET Program as well as the approach being followed to program management. The paper will also describe possible collaboration effects with other government programs (NASA, DOD).

Background

NASA and its predecessor, the National Advisory Committee for Aeronautics (NACA), have an 85 year tradition of developing and providing leading edge aeronautics technologies which have contributed to the U. S. industry (airframe and propulsion) leadership in the international aerospace marketplace. With the dawn of the new millennium, NASA has initiated a major new program, the Ultra-Efficient Engine Technology (UEET) Program that is positioned to continue the development and transfer of critical turbine engine technologies to the U. S. aeropropulsion industry. The UEET technologies will enable revolutionary increases in future propulsion system designs for both commercial and military applications. The UEET Program is positioned to continue the heritage of successful NASA aeropropulsion technology programs including:

1. Engine Component Improvement (ECI) Program
2. Energy Efficient Engine (E^3) Program
3. Quiet Clean Short Haul Experimental Engine (QCSEE) Program
4. Experimental Clean Combustion (EECP) Program
5. Advanced Turboprop Program (ATP)

The above programs conducted in the 1970-1980s timeframe enabled the U. S. industry to confidently design and bring to market products such as the GE90 and PW4000 series engines which are recognized to be industry leaders. In particular, NASA's $200M+ involvement in technology development in the late 1970s to late 1980s time period enabled U. S. industry to confidently invest over $2B in the development of commercial high bypass turbofan engines.

More recently, the High Speed Research (HSR) and Advanced Subsonic Technology (AST) programs continued this tradition through the decade of the 1990s. The wealth of the aeropropulsion technologies developed in the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
SEP 2000	**N/A**	**-**

4. TITLE AND SUBTITLE
NASAS Ultra-Efficient Engine Technology (UEET) Program/Aeropropulsion Technology Leadership For The 21st Century

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Glenn Research Center Cleveland, OH 44135

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002333. International Congress of Aeronautical Sciences (ICAS) (22nd) Held in Harrogate, United Kingdom on August 27-September 1, 2000. U.S. Government or Federal Purpose Rights License, The original document contains color images.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**11**	

HSR and AST Programs are already being utilized in a wide variety of commercial and military engine designs.

This paper will overview the UEET Program. In particular, the projected environmental impact of the growing commercial aviation fleet of the future will be overviewed which establishes the basis for the UEET vision, goals and investment strategy. Each of the investment areas will be overviewed and the opportunities for partnerships with other NASA and government programs will be described.

Projected Environmental Impact of Commercial Aviation

The projected increase in the demand for commercial air transportation in the 21st century is large. The publicly available projections by Boeing and Airbus indicate over 20,000 new commercial aircraft will be required of the next 20 years if this projected demand is to be met. This aircraft demand will translate into a turbine engine demand of over 40,000 units.

This significantly increased commercial aircraft fleet size will result in a corresponding increase in aircraft pollutants such as CO_2 and NO_x emitted in the atmosphere unless viable technology based solutions are developed now. Figure 1 shows the projected impact of this growing fleet on the amount of CO_2 emitted into the atmosphere. The projections done by NASA indicate the amount of CO_2 will grow by a factor of 3-4 over the 1990-2050 time frame if no vehicle/propulsion system improvements occurred. While Figure 1 describes the global environment impact of aviation, the local air quality concerns must also be considered.

Figure 2 shows the expected growth in our travel also results into an increased concern for local air quality around airports. NO_x emissions are predicted to increase by a factor of two to four times over the 1990-2010 time frame. Both the environmental Protection Agency and the European Union are pressuring the International Civil Aviation Agency (ICAO) for more stringent NO_x reduction standards. Some European airline customers are already requiring NO_x reduction levels of more than 60% below current ICAO standards to avoid paying significant landing fees at airports such as Zurich, Sweden.

The above provides a brief background for the need to develop technologies which will enable the 21st century commercial aviation fleet to have a significantly reduced impact on the environment and (both global and local), therefore, quality of life. NASA's role as a technology innovator is to look for revolutionary technologies which offer potential for quantum increases in performance of future aerospace vehicle designs. NASA's role is not to look for those technologies, which contribute to small, incremental change. These so-called product improvement efforts are more appropriately done by industry. However, the revolutionary technologies developed to address these environmental concerns cannot result in future turbine engine designs which are significantly more expensive to build and maintain. Simply stated the technologies must be affordable.

UEET Vision and Goals

The vision of the UEET Program is to develop and handoff revolutionary propulsion technologies that will enable future generation vehicles over a wide range of flight speeds.

While a vision sets a long-term direction by a program, it is the goals, which once properly chosen will allow the right technology investment decisions to be made. The UEET Program goals are:

1. Propulsion technologies to enable increases in efficiency and therefore, fuel burn reductions of up to 15% (equivalent reductions in CO_2).
2. Combustor technologies (configuration and materials) which will enable reductions in landing-take off (LTO) NO_X of 70% relative to 1996 ICAO standards.

While these goals are for future commercial aircraft (subsonic and supersonic) the aeropropulsion technologies required to meet these goals will be broadly applicable to a

much wider variety of turbine engine applications. In particular the technologies will have major positive impacts on future turbine engine based propulsion systems (commercial and military) across the Mach range (0 to hypersonic).

UEET Technology Selection/Evaluation Approach

The aerospace industry (government, industry, and academia) faces a very constrained budget environment for the foreseeable future. Thus, it is critical that a sound, disciplined decision process be utilized to select those technologies to pursue. The UEET Program is working closely with the NASA Intercenter Systems Analysis Team (ISAT) to evaluate the proposed technology investments as to their individual and combined contributions to meeting one or both of the UEET Program goals. The ISAT team was assembled by Agency management to evaluate the progress toward achieving the output objectives of NASA's three pillars strategic plan for aerospace technology development. NASA Langley Research Center is the lead center for the ISAT team.

The ISAT team is composed of airframe and propulsion systems analysts from Langley, Glenn, Ames, Marshall and Dryden Flight Research Centers. These individuals working in an Integrated Product Development Team (IPD) environment use leading edge system analysis/prediction tools and methodologies. The UEET Program Office provides the proposed technology efforts to the ISAT, and in turn ISAT provides the projected returns on technology investment to the UEET Program Office (see Figures 3a & 3b). These inputs are critical to the technology selections for inclusion in the UEET Program.

This close working relationship between the UEET and ISAT must continue throughout the life of the UEET Program. Specifically, the initial ISAT results are based on researcher input as to the projected outcome or contribution of individual technology effort as well as the uncertainly in outcomes. As the technology development effort begins and hard data is acquired, (the Technology Readiness Level (TRL) of the technology is increased) it is important that the projected contribution and uncertainty levels be adjusted accordingly and updated ISAT assessments be conducted. This ongoing reassessment of technology investment approach will allow the UEET Program management team to make the necessary rebalancing of investments throughout the life of the program. Also, it is important to keep aware of new technology investment opportunities and weigh them against technologies currently in the UEET Program. Again, the ISAT effort will provide key inputs for the program office evaluation and decision.

In addition, the ISAT process provides a critically important contribution to the risk management efforts for the UEET Program.

In order to understand the broader impact of the UEET technologies, a large number of reference propulsion systems and aerospace vehicles have been defined (Figure 4). The ISAT team will on a regular basis also evaluate the impacts of UEET technologies on these systems/vehicles. The results will in turn be provided to appropriate stakeholders and partners.

Technology Readiness Level Considerations

The technology readiness level (TRL) concept is a central consideration in NASA's Aerospace Technology Enterprise programs. Figure 5 depicts NASA's TRL scale including definitions as well as the key programmatic relationships. As the figure indicates, the span of technology coverage for the UEET Program is nominally 3 to 5. TRL5 technology validation tests of advanced components (e.g. combustor, compressor, turbine) will constitute key outputs of the UEET Program. The advanced technology concepts coming from the array of NASA Base R&T Programs (e.g. Aerospace Propulsion & Power) provide key technology inputs to the UEET Program. As such, the UEET and Base Programs can be viewed as technology partners. NASA and DOD are actively working together to determine appropriate technology transfer opportunities

between UEET and Integrated High Performance Turbine Engine Technology Program (IHPTET) of DOD. TRL6 technology demonstrations provide a critical step in the technology maturation process. These demonstrations are termed Integrated Component Technology Demonstrations (ICTD) for the UEET Program. These tests demonstrate conclusively that the technologies are viable and, therefore, can be utilized confidently by industry in follow on product insertion programs. While these demonstrations are not in the UEET baseline program, it is the UEET Program Office's intention to actively see (1) financial support and (2) government or industry risk sharing partners to conduct ICTD tests as appropriate. Opportunities exist for NASA and DOD to collaborate in many of these testbed opportunities. It is expected that existing engine hardware will be used wherever possible and appropriate to provide for the most cost effective ICTD tests.

High Fidelity System Simulation

NASA and the U. S. aeropropulsion industry are actively developing and validating simulation tools for multidisciplinary simulation and design of aerospace propulsion systems. The vision being pursued is one of the numerical test stand or wind tunnel. These simulation tools are critical to effecting considerable reductions in design cycle time and, therefore, cost of future systems.

The UEET Program will utilize these emerging tools to predict performance and operability of selected future turbine engine system designs utilizing UEET technologies. Figure 6 suggests the approach to be followed. As tools are developed by the NASA Numerical Propulsion System Simulation (NPSS) and the Intelligent Synthesis Environment (ISE) Programs, they will be utilized by UEET to analyze selected systems for a subsonic and supersonic cruise commercial, military, and hypersonic cruise/access-to-space applications. In each case appropriate key stakeholders and customers will be involved in the selection of the systems to be modeled.

Technology Investment Areas

Figure 7 depicts the six technology investment areas for the baseline UEET Program. The following sections will describe the technical content of each area.

Emissions

The AST and HSR Programs both developed and transferred to industry ultra-low emissions technologies for subsonic and supersonic commercial applications. In particular, the AST Program demonstrated combustor configurations, which achieved LTO NO_x reduction levels of 50 percent below the existing ICAO 1996 standards. The HSR Program demonstrated ultra low supersonic cruise NO_x levels of 4gm NO_x/kg fuel burned for a lean burn configuration in subscale sector tests.

The emissions research in the UEET Program will take the next major jump in ultra low emissions technology development. Concepts that appear to offer potential for at least a 70% LTO reduction will be evaluated in flame tube facilities at both government and industry locations. The government tests will be conducted in NASA Glenn's Advanced Subsonic Combustion Rig (ASCR). The ASCR facility allows for testing of combustion concepts at the proper temperatures and pressures of the significantly higher-pressure ratio engine cycles required to meet the UEET goals. Initial systems studies indicate pressure ratios of at lest 55:1 for large engines and 40:1 for small engines will be required. The ASCR facility is equipped with state-of-the-art diagnostics capabilities so the ASCR tests will shed new light on the physics of ultra low emissions combustion.

The most promising combustion concepts will then be carried into follow-on sector and annular rig tests that will validate technology readiness at the TRL5 level. Advanced diagnostics will be used as appropriate to provide insight into the key physical processes.

In addition to measurement of NO_x levels in the flame tube, sector, and annular rig tests, measurements will also be made of the particulate and aerosol pollutant levels.

Growing evidence exists in the international atmospheric science community (ref. 1) that aerosols and particulates are key contributors to contrail development, which leads to cirrus cloud development. Cirrus cloud increase due to aviation is projected to have a significant future impact on radiative forcing and therefore global warming. The significant particulate and aerosol database to be developed in the UEET Program will be a key input into future scientific studies of the atmospheric effects of aviation.

The UEET Program will also take advantage of the rapidly emerging capabilities to accurately model the fluid physics of combustion in computer codes such as the National Combustor Code (NCC) being developed by NASA. The NCC code will be used to predict the emissions characteristics for the flame tube, sector, and annular rig configurations. Appropriate instrumentation will be employed in the tests to acquire code validation data. The UEET Program should provide users with increased confidence that the NCC code can be used as a reliable analysis/design tool for future low emissions combustor designs.

Highly Loaded Turbomachinery

This UEET investment area will focus on developing turbomachinery technologies for lighter weight, reduced stage cores, low pressure (LP) spools, and propulsion for high-performing, highly efficient, and environmentally-compatible propulsion systems. Concepts will be explored that could yield significantly increased levels of aerodynamic loading, trailing edge wake control, and higher levels of cooling effectiveness. A variety of flow control concepts will be explored for application to fans, compressors, and turbines. Downselects will occur, and the most promising approaches will be evaluated through proof-of-concept tests. The results of the proof-of-concept tests along with the results of numerical simulations based upon physics-based models developed in the UEET Program will guide the design of hardware for individual component tests (i.e., fan, compressor, and turbine) to reach a technology readiness level of 5.

Like the emissions investment area, the highly loaded turbomachinery investment area will build up on some efforts begin in the AST and HSR Programs as well as the APP Base Program. However the sub program goals for this investment area, namely:

- Projected 20% weight reductions in turbomachinery components
- Increase of 1-2% in component efficiency
- Increase in stage loading of 50%
- Increase in turbine rotor inlet inlet temperature of 400°F (with commercial life)
- Reduction in cooling airflows of 25%

require revolutionary advances in turbomachinery technologies.

Materials and Structures for High Performance

The high temperature engine materials and structures technologies developed in this investment area will make significant contributions to both UEET Program goals. Technologies developed include Ceramic Matrix Composite (CMC) combustor liner and turbine vane, advanced turbomachinery disk alloys, turbine blade material systems, high temperature polymer matrix composites (PMC) and innovative lightweight materials and structures for static structures of future turbine engine based propulsion systems.

Ultra low levels of NO_x reduction in advanced combustor concepts requires reducing cooling air by at least 10-15 percent relative to current designs. Reduced amounts of cooling results in higher combustor linear temperatures. Recent propulsion system studies indicate liner surface temperature capability on the order of 2700°F will be required for the advanced engine cycles being considered. Metallic liners cannot withstand such temperature levels and still have commercial life. A CMC material with the required characteristics will be developed and demonstrated in laboratory and full annular rig tests. This effort will build upon the CMC work done in the HSR program. However, the significant increase in temperature requirements

(approximately 500^{o}F) suggests the magnitude of the technical challenge being undertaken in the UEET Program.

CMC turbine vane concepts will be evaluated using the same material discussed above in conjunction with a compatible thermal barrier coating (TBC) and employing advanced manufacturing techniques to be developed in the UEET Program. Rig tests (TRL4) will be conducted of most promising turbine vane concept.

Achieving the aggressive fuel burn reduction goal of 8-15 percent requires that the engine cycles have higher levels of turbine inlet temperatures and reduced system weight. Currently, overall cycle pressure ratio is limited by the temperature capability of the turbomachinery disk material. Advanced disk alloys will be developed with properties required for engine overall pressure ratios of 55:1 and turbine rotor inlet temperature (TRIT) capability of 3100^{o}F.

The properties of the advanced disk alloy developed will be demonstrated in commercial engine size forgings. The disk alloy effort will build on the efforts conducted in the HSR Program.

A TRIT goal of 3100^{o}F combined with a 15-25 percent reduction in cooling airflow are also required to support the program's 8-15 percent fuel burn reduction goal. The emphasis of the effort in the UEET Program will be on developing advanced TBCs which are compatible with the single crystal nickel based alloy also developed in the HSR Program. The goal of the TBC effort is a 300^{o}F increase in temperature capability over current state-of-the-art coatings.

Innovative lightweight material and structural concepts for static structures are also required to support the fuel burn reduction goal. Engineered structures specifically designed for each subcomponent are projected to have potential for significant weight reduction. Examples of engineered structures, which will be evaluated, include porous and cellular materials as well as honeycomb structures. These concepts have already been evaluated for low temperature applications. The UEET Program will develop appropriate technologies, which will extend the engineered structure concept to high temperature applications utilizing nickel-based superalloys and gamma TiAl. In addition, the feasibility of utilizing CMCs for three dimensional subcomponent structures will be evaluated. The most promising lightweight concepts will be evaluated in appropriate subcompoenent rig tests (TRL3-4).

Intelligent Propulsion Controls (IPC)

The rapid explosion of information technologies (IT) makes it possible to envision future autonomous propulsion system designs which allow the control system to independently of pilot interaction maximize performance across the particular mission profile while at the same time minimizing environmental impact. Such a control system could also adjust system characteristics so as to maximize individual component life and, therefore, improve propulsion system life and safety. Currently, the IPC area is being planned with the challenge being to find the proper integration of information, propulsion and integrated flight propulsion control technologies.

Propulsion-Airframe Integration (PAI)

The PAI investment area will develop advanced technologies that will allow low drag propulsion system integration for a wide variety of aerospace vehicle classes. Decreasing drag improves vehicle performance and efficiency thereby directly contributing to the UEET fuel burn reduction goal.

The PAI effects will focus on tools and techniques for optimum nacelle placement and shaping. The effects will be both experimental and computational.

The analytical efforts will emphasize the development and validation of a CFD technique based upon the unstructured grid approach coupled to an adjoint optimization technique. Once validated against appropriate experimental data to be acquired in the UEET Program, the tool will allow aircraft designers to more reliably determine the proper location and design of the propulsion system nacelle.

Advanced configurations, both commercial and military, will feature reduced length inlets with highly three-dimensional internal flowfields as well as boundary layer ingestion. Thus, a major technical challenge becomes how to not only prevent flow separation but also manage the internal flowfield characteristics so as to ensure a high quality flow is presented to the propulsion system.

The PAI effort will develop the necessary active control technologies through evaluation of a number of sensors and actuators, which could be used to detect and control separation. Active control concepts based upon compliant materials will also be evaluated. The most attractive approaches will be demonstrated in a wind tunnel test of a selected inlet configuration (TRL5).

Systems Integration and Assessment

The systems integration and assessment investment area will take the technologies from the other investment areas and integrate them into conceptual systems. Evaluations will be completed on a regular basis for a variety of reference propulsion systems and aerospace vehicles to assess the impacts of individual technologies and how the technologies combine to meet program goals. These efforts are closely related to the ISAT activities previously discussed. However, the UEET specific integration studies will be much more detailed and as such will allow technology trade studies to be conducted.

In addition, regular environmental impact studies will be concluded. The projected impact of engine exhaust products on changes to the global atmospheric composition and distributions will be determined using state of the art two and three dimensional predictions models developed under the sponsorship of the HSR/AST Programs. The engine cycles utilized in these studies will be developed utilizing UEET technologies so that reduced environmental impacts of propulsion systems using UEET technologies can be determined.

Also, high fidelity, multi disciplinary system simulations will be performed incorporating UEET technologies in order to better understand the complex component interactions.

Concluding Remarks

This paper has overviewed the UEET Program. The program will continue the heritage of NASA aeropropulsion technology development and transfer to the U. S. aerospace industry. The investment strategy emphasizes revolutionary technologies, which promise to enable future generation propulsion system designs, which will exhibit major performance improvements while having significantly less impact in the environment.

References

[1] Aviation and the Global Atmosphere. Published for the Intergovernmental Panel on Climate Change. Cambridge University Press 1999.

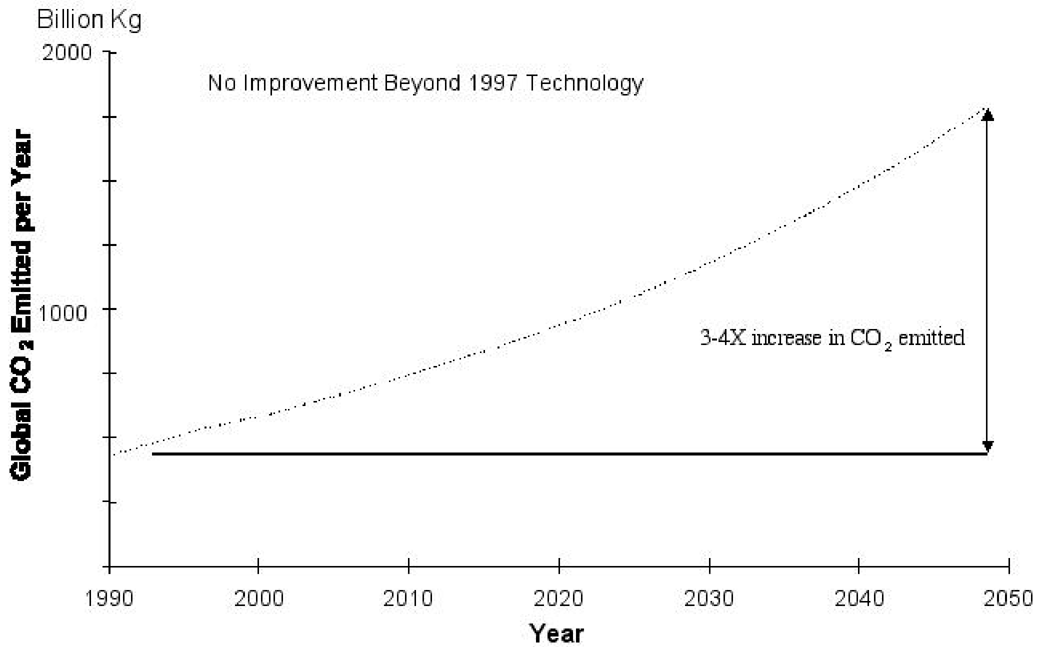


Figure 1. Projected Increase in CO_2 Emissions

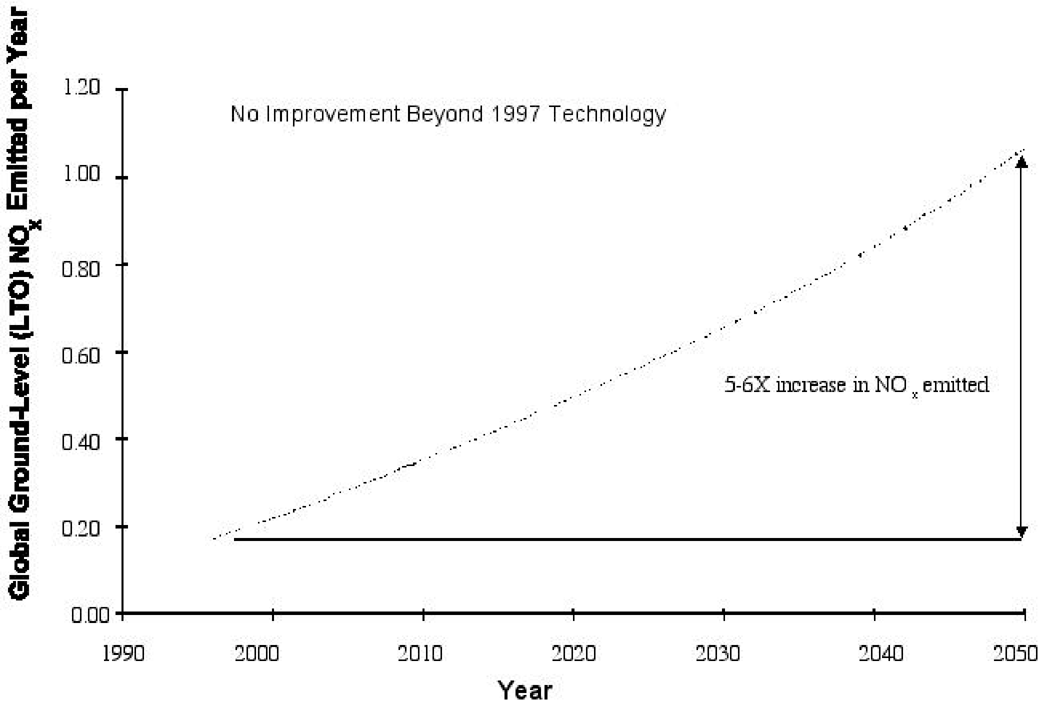
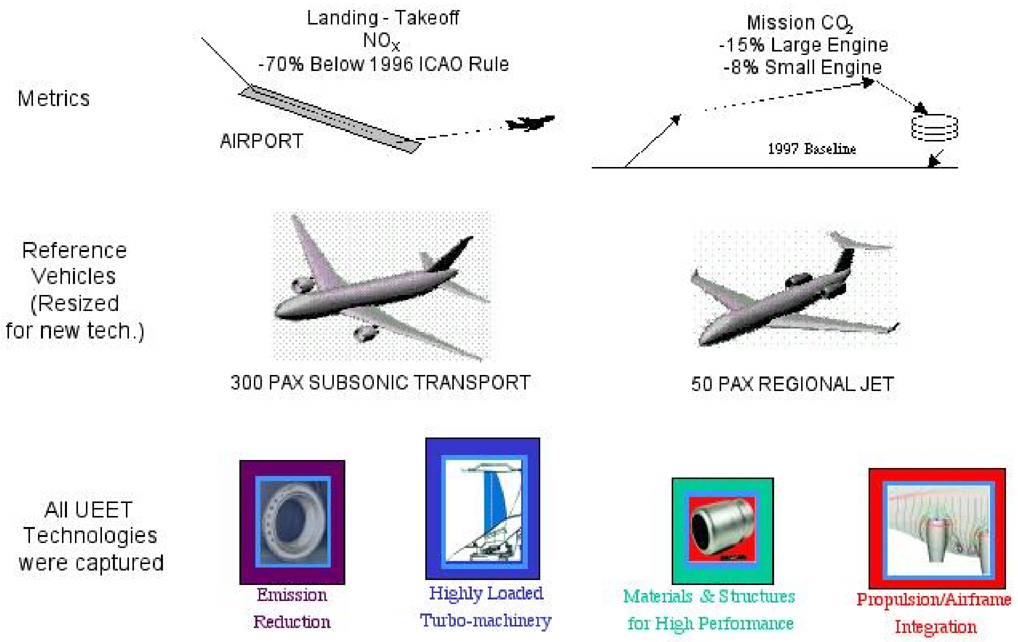
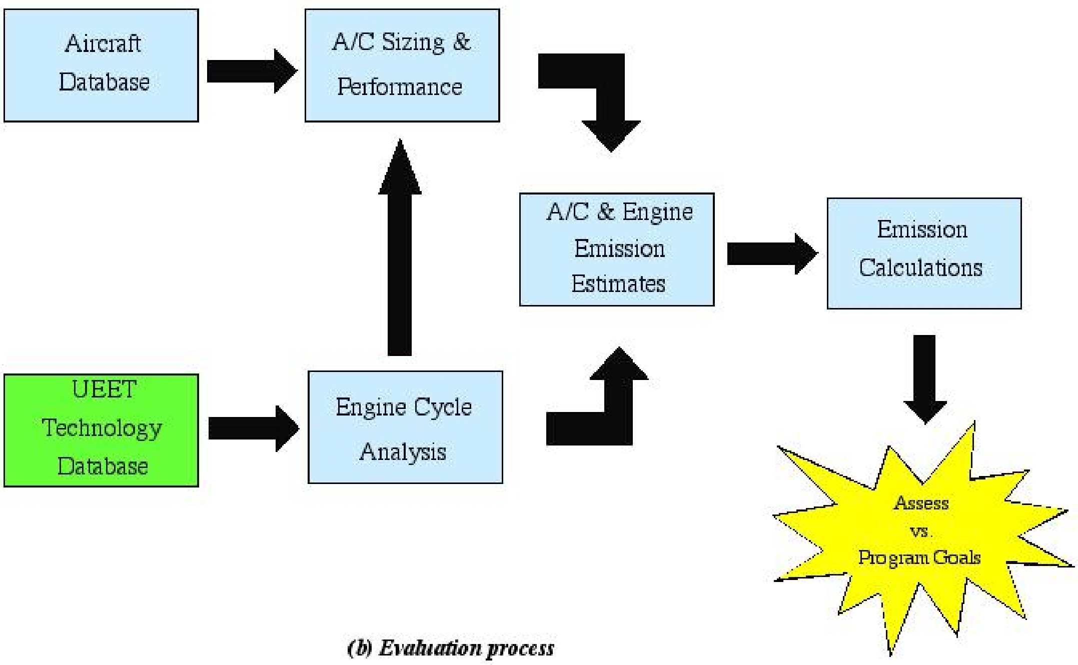


Figure 2. Projected Increase in LTO NO_X



(a) Hierarchy of approach
Figure 3. ISAT Assessment Approach



(b) Evaluation process
Figure 3. ISAT Assessment Approach

Figure 4. Reference vehicles and propulsion systems used to assess UEET technology benefits .

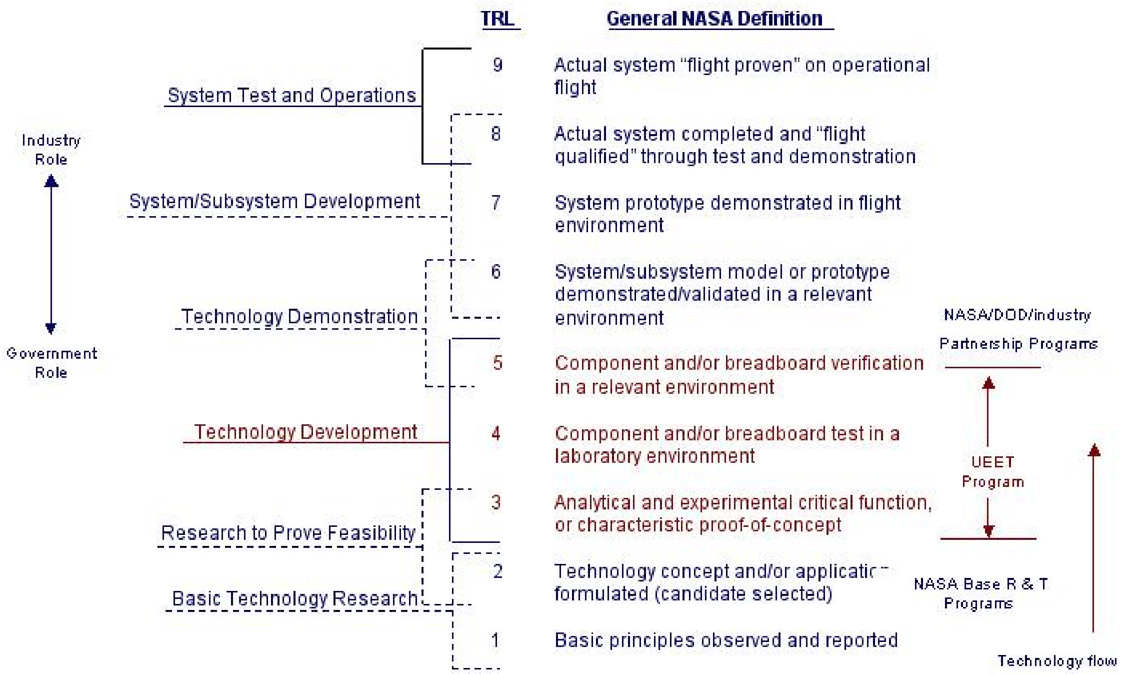


Figure 5. NASA Technology readiness scale

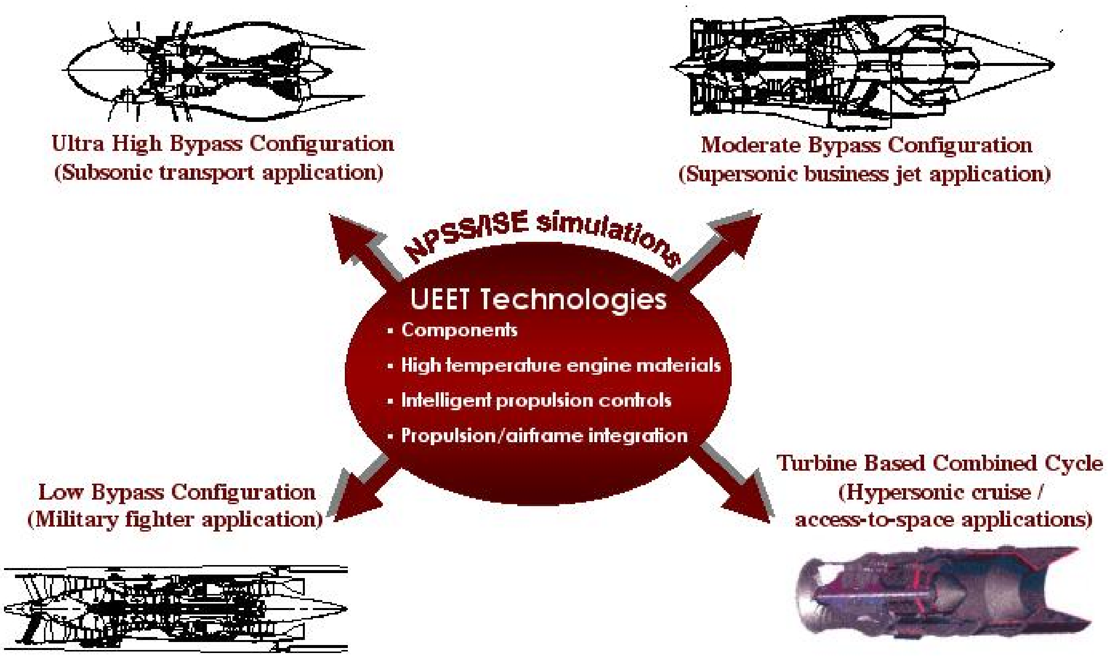


Figure 6. Use of simulation tools to model advanced turbine engine propulsion systems.

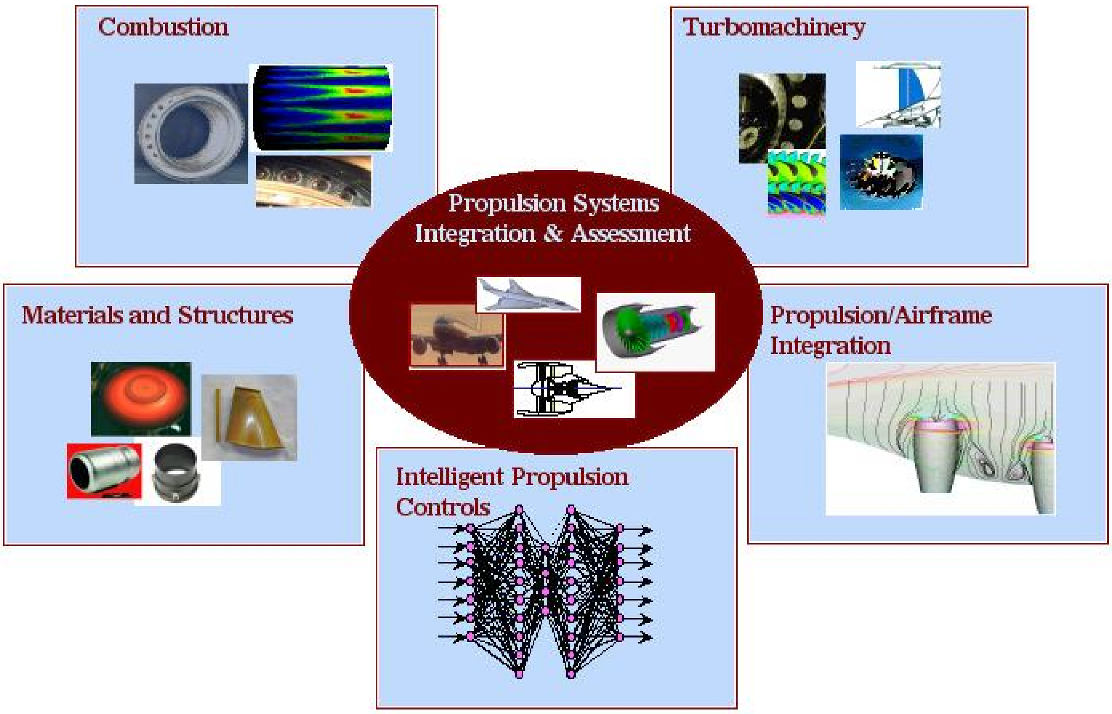


Figure 7. UEET program technology investment areas.